Nutrient Uptake in Plant Parts of Sixteen Forages Fertilized with Poultry Litter: Nitrogen, Phosphorus, Potassium, Copper, and Zinc

Gary A. Pederson,* Geoffrey E. Brink, and Timothy E. Fairbrother

ABSTRACT

Poultry litter used as fertilizer for forages often results in nutrient accumulation in soils over time. Maximizing nutrient uptake by forages would facilitate nutrient removal from litter-treated soils when the plants are mechanically harvested. This study compared N, P, K, Cu, and Zn concentrations and distribution in plant parts of annual ryegrass (*Lolium multiflorum* Lam.) with 15 other cool-season forages fertilized with poultry litter. Annual ryegrass, three cereals, and 12 legumes were seeded in a pasture at Collins, MS, on a Savannah fine sandy loam (fine-loamy, siliceous, semiactive, thermic Typic Fragiudult) fertilized with poultry litter. Each species was harvested at full maturity and separated into root, stem, leaf, and flower components, and N, P, K, Cu, and Zn concentration and content of each component was determined. Most legumes had greater P, Cu, and Zn concentrations than annual ryegrass in many plant parts. Content of P, Cu, and Zn was similar between annual ryegrass and legumes due to greater dry matter yield of annual ryegrass compared with legumes. Stems, especially oat (*Avena sativa* L.) stems, had the lowest N/P ratio of all plant parts, which was more comparable to the N/P ratio of poultry litter. Nitrogen concentration was highly correlated with P, Cu, and Zn concentrations in aboveground plant parts, suggesting that improvements in N fertility would improve P, Cu, and Zn concentration in plants. To maximize P uptake in poultry litter–fertilized forages, management practices and breeding objectives should concentrate on optimizing stem production, while maintaining palatability, because almost 60% of total P in forages is located in stems.

PASTURES AND HAYFIELDS are common sites for poultry and broiler litter applied as fertilizer on forages used for cattle (*Bos taurus*) grazing or hay production in the southeastern USA. Cattle grazing removes relatively few nutrients from the farm through milk or meat production (Ball et al., 1991). Amounts of nutrients taken up by plants are similar to nutrient amounts released from manure deposited back on the pasture by animals grazing the plants. Removal of mechanically harvested forage from the farm will reduce the buildup of nutrients in soil fertilized with litter. Traditionally, forages have been fertilized with litter to meet the plant N requirements. However, litter applied to meet plant N requirement contains more P than required by the plant, and P buildup in the soil will occur (Kingery et al., 1993; Sharpley et al., 1998). In many counties of southern states, P from manure meets or exceeds plant uptake (Potash and Phosphate Inst., 1998). The effect of this excess P on water quality is becoming a major concern both nationally and internationally (Sharpley et al., 1998). However, N and P are not the only components of animal manure that can cause environmental concern. Interest has recently developed in accumulation of heavy metals such as Cu and Zn in soils fertilized with animal waste.

The concentration of Cu and Zn in animal waste varies due to the type of animal and feeding practices. Poultry and swine feeds contain greater amounts of Cu and Zn than dairy and beef cattle feeds (Nicholson et al., 1999). Utilization of these heavy metals by poultry can be relatively low. Mohanna and Nys (1999) reported that only 6% of Zn ingested by poultry is retained. Concentration of Cu and Zn in poultry litter can vary widely due to differences in poultry feed and pest control (van der Watt et al., 1994; Pesti and Bakalli, 1996). In a review article, Sims and Wolf (1994) reported mean litter concentrations vary from 32 to 593 mg Cu kg^{-1} in 12 studies and from 125 to 496 mg Zn kg^{-1} in seven studies. Amounts of Cu and Zn applied to the soil in poultry litter exceed the annual nutrient requirements of plants, with estimates of 6.6 times more Zn applied than plants require (Mohanna and Nys, 1999).

Short- and long-term applications of poultry litter increase Cu and Zn concentrations in soil, especially in the top 5 to 10 cm (Wood and Hattey, 1995; Wood et al., 1996; Han et al., 2000). Litter applications for 15 to 28 yr resulted in greater Cu and Zn accumulation down to 45 cm compared with non-litter-treated controls (Kingery et al., 1994). Concentrations averaged 2.6 and 10 mg kg^{-1} Cu and Zn, respectively, in the top 15 cm of soil following these long-term applications compared with 0.7 and 2.1 mg kg^{-1} Cu and Zn, respectively, without litter application. Plant uptake of heavy metals can be quite low, with only 0.5% of Cu and 3 to 5% of Zn applied in poultry litter taken up by sorghum-sudangrass, *Sorghum bicolor* (L.) Moench (van der Watt et al., 1994).

Reports of nutrient uptake from soils treated with animal wastes have considered relatively few forage species. Most studies have used a single species or mixture of species as a catch crop while evaluating other treatment variables (e.g., Vervoort et al., 1998). Abe and Ozaki (1998) reported that annual ryegrass had the

G.A. Pederson, USDA-ARS, Plant Genet. Resour. Conserv. Unit, 1109 Experiment St., Griffin, GA 30223-1797; and G.E. Brink and T.E. Fairbrother, USDA-ARS, Crop Sci. Res. Lab., Waste Manage. and Forage Res. Unit, P.O. Box 5367, Mississippi State, MS 39762. Contrib. of the USDA-ARS in cooperation with the Mississippi Agric. and Forestry Exp. Stn. Received 1 June 2001. *Corresponding author (gpederson@ars-grin.gov).

Published in Agron. J. 94:895–904 (2002).

Abbreviations: DM, dry matter.

greatest P and N removal rate of 11 spring-grown species in plant beds used to filter wastewater. Honeycutt et al. (1988) reported that dry matter (DM) yield of bermudagrass [*Cynodon dactylon* (L.) Pers.], tall fescue (*Festuca arundinacea* Schreb.), and a tall fescue–red clover (*Trifolium pratense* L.)–white clover (*T. repens* L.) mixture was increased with increasing rates of poultry litter. Plant N and P uptake increased with rate of poultry litter application on bluegrass (*Poa pratensis* L.)–tall fescue and bermudagrass–tall fescue pastures (Lucero et al., 1995; Vervoort et al., 1998). Long-term litter application on tall fescue pastures increased plant N, P, and K concentration (Kingery et al., 1993). Forages, such as tall fescue, have been promoted for use as vegetative filter strips on litter-fertilized sites to decrease runoff containing heavy metals (Edwards et al., 1997; Sauer et al., 1999). However, tall fescue grown in pastures with a history of long-term litter application had similar Cu and Zn concentrations as fescue grown in pastures without litter application (Kingery et al., 1994). There is a wide range of forage species that are adapted for growth in the southeastern USA (Ball et al., 1991), but little is known about the nutrient uptake of these species under poultry litter fertilization.

Distribution of nutrients within plant parts varies among species. Nitrogen (crude protein) concentration was lowest in leaves and highest in stems of subterranean clover (*T. subterraneum* L.) in comparison with three other clovers (Brink and Fairbrother, 1992). Maize (*Zea mays* L.) lines selected for improved P uptake had larger root systems with greater P accumulation than lines with lower P uptake rates (Ciarelli et al., 1998). Increases in P supply decreased the root/shoot ratio in three of four forage legumes (Hart et al., 1981). Management can also alter nutrient uptake by the modification of variables such as litter application rates, application time, or plant maturity at harvest.

Annual ryegrass is most commonly grown for winter pasture and is sometimes used for hay and silage in the southeastern USA, often overseeded on bermudagrass (Ball et al., 1991). The objectives of this study were to (i) compare N, P, K, Cu, and Zn concentration, uptake, and distribution in roots, stems, leaves, and flowers of annual ryegrass with 15 other cool-season forage grass and legume species fertilized with poultry litter and (ii) determine which plant part is most important to emphasize in breeding and management efforts to maximize nutrient removal from sites fertilized with poultry litter.

MATERIALS AND METHODS

A total of 16 forages consisting of four grasses, two perennial legumes, and 10 annual legumes were evaluated in this study. The grasses were annual ryegrass and three cereals: oat, rye (*Secale cereale* L.), and wheat (*Triticum aestivum* L. emend. Thell.). The perennial legumes were red clover and white clover. The annual legumes were arrowleaf clover (*T. vesiculosum* Savi), ball clover (*T. nigrescens* Viv.), berseem clover (*T. alexandrinum* L.), crimson clover (*T. incarnatum* L.), persian clover (*T. resupinatum* L.), rose clover (*T. hirtum* All.), subterranean clover, austrian winter pea [*Pisum sativum* var. *arvense* (L.) Poir.], caley pea (*Lathyrus hirsutus* L.), and hairy vetch (*Vicia villosa* Roth). All species were treated as winter annuals. This study was a companion study to results reported by Brink et al. (2001) wherein these species were evaluated for nutrient uptake in a single-cut hay and forage production system in a separate portion of each plot.

Seed of the 16 forages were broadcast-seeded in 2- by 5-m plots with 1-m alleys between replications in September 1996 and 1997. Seeding rates were reported in Brink et al. (2001). The study was conducted on a Savannah fine sandy loam using a prepared seedbed in a pasture at Collins, MS (31.6° N, 89.6° W). Soil chemical characteristics using the Mehlich 3 extractant (Mehlich, 1984) are presented in Table 1 along with pH in 1:1 soil/water suspension. The pasture had a history of annual broiler litter applications, with additional litter applied at 9 Mg ha^{-1} (N, 34; P, 20; and K, 32 g kg^{-1} litter and Cu, 82 and Zn, 504 mg kg^{-1} litter) and incorporated to about 15 cm before seeding.

Each species was harvested once at full maturity, defined as full bloom for the legumes and soft-dough stage for annual ryegrass and the cereals, to maximize forage production and possible nutrient removal, though at the expense of forage quality and palatability. The harvesting dates for the species ranged from 2 Apr. to 3 June 1997 and 9 Apr. to 29 May 1998. Plants were dug from a 0.5- by 0.5-m quadrat randomly placed within each plot in an area free of significant volunteer weed infestation. The plants were dug sufficiently deep to extract the entire root system contained within the quadrat for each species. Loose soil on the roots was removed in the field. Following harvest in the field, all samples were maintained under cold storage (7°C) before washing and separation into plant parts.

Samples were separated into roots, stems, leaves, and flowers. All remaining soil and organic matter was washed from the root system. Roots were severed from the aboveground plant parts at the junction of root and stem or stolon. Each legume flower head and grass inflorescence was separated from the stem at the point of the bottom floret. Leaves (including petioles) of legume species and leaf blades (without the leaf sheath) of grasses were removed from the stem. Stems were defined as the remaining plant part following removal of flowers, leaves, and roots. All plant parts were dried at 65°C for 48 h and weighed.

Samples were ground to pass through a 1-mm screen. Phosphorus, K, Cu and Zn concentrations were measured using an inductively coupled argon plasma emission spectrophotometer using methods given in Brink et al. (2001). Nitrogen concentration was determined by macro-Kjeldahl. Nitrogen, P, K, Cu, and Zn content of the plant parts was calculated as a product of dry weight and N, P, K, Cu, or Zn concentration,

Table 1. Soil test nutrient levels at initiation of experiment each year.

	Sample depth	pH	P	K	Ca	Cu	Fe	Mg	Mn	Zn
	cm		mg kg^{-1} soils							
1996	0–15	5.1	55	63	674	12.4	361	68	154	4.6
	15–30	5.5	5	49	709	5.6	123	83	72	1.5
1997	0–15	5.5	62	39	815	12.2	382	75	186	4.2
	15–30	5.7	1	26	580	3.8	117	54	98	0.7

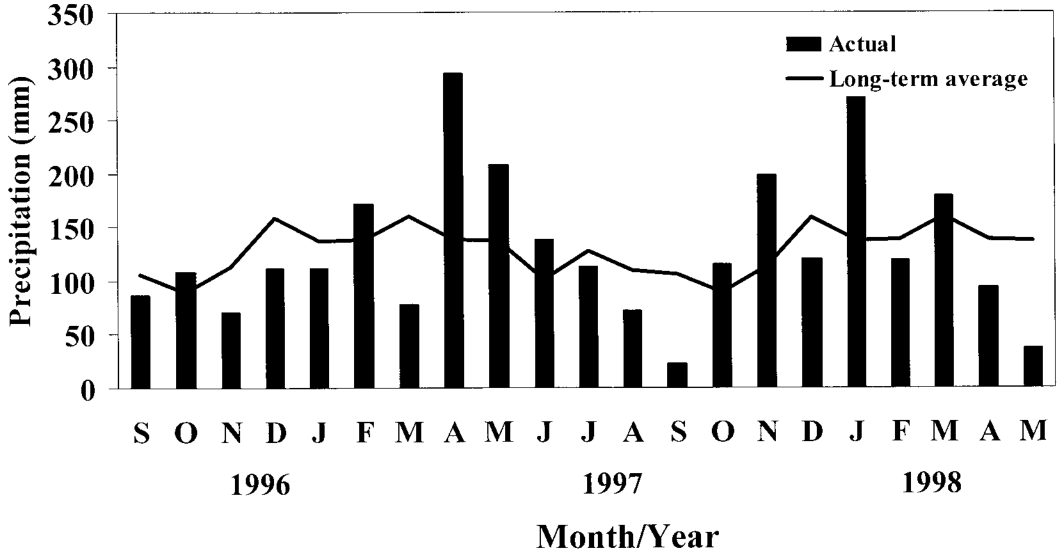

Fig. 1. Actual and long-term average monthly precipitation at Collins, MS, during the duration of the experiment.

respectively. Nitrogen/P ratio was computed from the N and P content data.

Experimental design was a randomized complete block with four replicates. Data were analyzed by analysis of variance (SAS Inst., 1990). Means of annual ryegrass were compared with those of the other species by Fisher's protected least significant difference (LSD) when means were found to be significantly different by the ANOVA *F*-test. Unless otherwise noted, the 0.05 level of probability was used to identify differences.

RESULTS AND DISCUSSION

Precipitation varied between the 2 yr of the study (Fig. 1). In the first year, a dry winter and early spring was followed by a wet April, May, and June. In the second year, a wet fall and winter was followed by a dry April and May. The precipitation differences resulted in a greater whole-plant DM yield in 1997 (535 g m^{-2}) than in 1998 (457 g m^{-2}). Year and year × species differences were significant for whole-plant DM yield, nutrient concentration, and nutrient uptake for most plant parts and most nutrients. Therefore, all data presented in this study were analyzed separately by year.

Annual ryegrass had the greatest whole-plant DM yield in 1997 (1090 g m^{-2}; Table 2). The four grasses averaged 823 g m^{-2} while the 12 legumes averaged 464 g m^{-2}. Among the legumes in 1997, crimson, red, arrowleaf, ball, rose, and berseem clover had the greatest total DM yields. In 1998, the four grasses had the greatest DM yield, with no differences among the grasses. The grasses averaged 969 g m^{-2}, and the 12 legumes averaged 306 g m^{-2}. Most DM yields were similar among the legumes in 1998, with only ball, berseem, persian, and white clover having lower yields than the other legumes.

Nitrogen

Nitrogen concentration in plant tissue is related to the method by which plants obtain N. In grasses, N

Table 2. Dry weight of plant parts of annual ryegrass, three cereals, and 12 legumes.

	1997				1998			
Forages	Stems	Leaves	Flowers	Roots	Stems	Leaves	Flowers	Roots
	g m^{-2}							
Annual ryegrass	645	259	33	153	564	245	64	178
Cereals								
Oat	426	202	74	45	578	287	52	119
Rye	486	142	67	63	637	106	78	113
Wheat	412	177	46	62	551	165	50	90
Legumes								
Austrian winter pea	192	63	9	3	211	78	4	5
Arrowleaf clover	423	168	33	34	298	62	30	18
Ball clover	350	194	18	34	178	35	7	16
Berseem clover	380	114	33	30	81	5	1	5
Caley pea	126	48	20	6	157	43	68	3
Crimson clover	375	276	88	36	286	101	34	13
Hairy vetch	341	58	13	10	352	44	13	10
Persian clover	117	59	14	11	71	7	1	4
Red clover	293	249	15	114	204	112	19	69
Rose clover	311	156	77	30	222	45	95	4
Subterranean clover	141	215	36	34	264	149	14	43
White clover	55	114	1	55	109	38	1	42
LSD 0.05	143	82	22	23	151	44	20	48

Table 3. Nitrogen concentration of plant parts of annual ryegrass, three cereals, and 12 legumes.

Forages	1997 Stems	1997 Leaves	1997 Flowers	1997 Roots	1998 Stems	1998 Leaves	1998 Flowers	1998 Roots
	g kg^{-1}							
Annual ryegrass	7.0	13.4	20.0	8.6	7.4	15.0	20.8	10.1
Cereals								
Oat	7.8	14.1	17.8	7.7	8.6	13.7	19.2	7.5
Rye	12.0	22.7	25.6	10.1	9.2	19.7	27.3	10.0
Wheat	10.9	22.0	21.6	8.3	11.0	16.1	22.9	8.3
Legumes								
Austrian winter pea	25.7	44.5	–†	–	24.9	49.6	65.1	26.6
Arrowleaf clover	14.9	38.4	38.5	21.0	15.4	35.6	34.1	23.7
Ball clover	19.6	40.3	46.2	–	23.6	48.9	42.2	21.6
Berseem clover	19.5	40.9	42.1	30.5	19.7	32.2	–	27.3
Caley pea	26.7	46.2	46.3	–	19.2	40.7	43.9	24.6
Crimson clover	18.1	34.6	34.4	24.8	19.1	39.8	30.9	23.2
Hairy vetch	23.0	55.2	–	–	24.1	53.9	56.2	22.1
Persian clover	15.2	34.6	44.2	–	21.5	31.5	41.0	26.5
Red clover	17.3	37.2	35.4	25.0	16.5	39.2	36.5	25.3
Rose clover	15.2	32.2	22.6	18.3	17.9	30.9	20.1	15.5
Subterranean clover	23.8	35.1	36.7	25.6	28.6	38.8	38.9	22.6
White clover	32.1	39.4	–	25.9	33.5	34.4	–	26.7
LSD 0.05	2.4	3.7	2.9	2.2	3.3	4.2	4.4	4.0

† Sample size too small to run N analysis.

concentration is determined by plant uptake and depends on the level of available N in the soil. In legumes, the amount of N taken up by the plant also depends on the level of available N in the soil. Fixation of N by rhizobia in nodules on legume roots provides the rest of the N needed, resulting in legumes having a more constant N status regardless of soil N availability. In high N fertility conditions, legumes may obtain a majority of their N through uptake rather than fixation, with N fixation accounting for as little as 25% of the plant N concentration (Schertz and Miller, 1972; Ledgard et al., 1996). The ratio of N uptake to fixation varies according to legume species, soil fertility, nodulation effectiveness, and environmental conditions (Mallarino and Wedin, 1990; Boller and Nosberger, 1994; Panciera and Sparrow, 1995).

In this study, the N concentration of annual ryegrass plant parts was less than that of all legume plant parts (Table 3). Legume stems averaged two to four times, leaves 2.5 to four times, flowers one to three times, and roots two to 3.5 times greater N concentration than annual ryegrass (Table 3). These results on plant parts support common knowledge of higher N and crude protein concentration in harvested portions of legumes compared with grasses (Minson, 1990; Ball et al., 1991). The greatest N concentration was observed in legume leaves and flowers, especially hairy vetch in 1997 and austrian winter pea leaves and flowers in 1998 (Table 3). The relative N concentration among plant parts within a legume species or comparisons among legume species were relatively consistent with previous reports (Harper, 1962; Davies et al., 1968; Minson, 1990; NRCS, 1992).

Whole-plant N content (N concentration × DM yield) of some legumes was also greater than annual ryegrass. In 1997, crimson, red, and ball clover had a greater whole-plant N content (average 17.6 g N m^{-2}) than annual ryegrass (10.0 g N m^{-2}). In 1998, subterranean clover (14.6 g N m^{-2}) had a greater whole-plant N content than annual ryegrass (11.0 g N m^{-2}).

Rye and wheat also had a greater N concentration than annual ryegrass in some plant parts. Rye leaves, wheat stems, and rye flowers had a greater N concentration than annual ryegrass in both years (Table 3). In 1997, rye stems and wheat leaves had a greater N concentration than annual ryegrass. There were no differences between annual ryegrass and the cereals for root N concentration or whole-plant N content.

Averaged over all species, leaves (34.6 g kg^{-1}) and flowers (30.7 g kg^{-1}) had greater N concentrations than stems (18.7 g kg^{-1}) and roots (19.2 g kg^{-1}). These results support previous reports that forage leaves have twice the crude protein (N concentration × 6.25) concentration of stems (Minson, 1990; Buxton and Mertens, 1995).

Phosphorus

Subterranean and white clover had greater P concentration in stems than annual ryegrass in 1997 while 8 of 12 legumes had greater P concentration in stems than annual ryegrass in 1998 (Table 4). Stems of subterranean and white clover are prostrate stolons, which are not harvested because they spread along the soil surface. Though these stolons may contain a significant P concentration, it is only a temporary sink as eventual death and decomposition will release the P back to the soil. Most literature on P concentration in forages deals with the harvested portion of the plant, which would include upright stems, leaves, and flowers. Results on harvested forage by Minson (1990) were similar to the results on stems of this study, as legumes averaged 3.2 g P kg^{-1} while grasses averaged 2.7 g P kg^{-1}. These results differed from the range of forages listed by the Natural Resources Conservation Service (1992) where harvested parts of legumes averaged 2.2 g kg^{-1} and grasses averaged 3.6 g kg^{-1}. Under high P fertilization, Jackson et al. (1964) reported a range of 2.6 to 4.2 g kg^{-1} in the harvested portion of alfalfa, white clover, subterranean clover, and red clover.

The greater stem dry weight of grasses resulted in

Table 4. Phosphorus concentration of plant parts of annual ryegrass, three cereals, and 12 legumes.

Forages	1997 Stems	1997 Leaves	1997 Flowers	1997 Roots	1998 Stems	1998 Leaves	1998 Flowers	1998 Roots
	g kg^{-1}							
Annual ryegrass	2.18	1.80	2.75	0.92	1.78	2.29	4.02	0.92
Cereals								
Oat	2.86	2.21	2.50	0.85	3.60	2.39	3.48	2.10
Rye	2.68	2.72	3.11	1.35	2.45	2.15	4.35	1.25
Wheat	2.42	3.01	2.94	1.19	2.14	2.41	3.82	1.14
Legumes								
Austrian winter pea	2.40	3.15	4.90	0.90	3.96	5.82	9.10	3.30
Arrowleaf clover	2.05	2.64	4.55	2.65	2.24	3.49	4.58	3.44
Ball clover	1.99	2.79	5.88	1.79	3.45	5.00	5.90	3.38
Berseem clover	2.12	2.66	5.08	3.32	2.29	1.95	–†	2.45
Caley pea	2.78	3.18	4.27	2.40	2.40	3.20	5.25	2.30
Crimson clover	2.29	1.99	3.49	2.86	3.36	3.74	4.79	3.65
Hairy vetch	2.09	3.49	8.03	2.28	3.50	5.66	7.10	2.45
Persian clover	1.80	2.42	5.67	3.45	2.96	2.55	5.10	4.40
Red clover	1.99	2.56	3.85	2.92	2.05	3.38	3.77	4.26
Rose clover	2.24	2.48	2.14	2.75	2.64	3.06	3.08	3.10
Subterranean clover	6.12	2.95	4.40	5.36	6.89	4.46	5.15	7.59
White clover	4.05	3.66	2.40	3.48	4.02	4.44	–	3.95
LSD 0.05	0.76	ns	0.98	0.82	0.76	1.08	1.12	1.10

† Sample size too small to run P analysis.

higher P content in grass stems than in legume stems. Grass stems averaged 1.25 g P m^{-2} in 1997 and 1.43 g P m^{-2} in 1998 while legumes averaged 0.57 g P m^{-2} in 1997 and 0.67 g P m^{-2} in 1998. In 1997, the P content in annual ryegrass stems was greater than in stems of any legume. Only subterranean clover stems had a greater P content in 1998 than annual ryegrass stems.

Oat had a greater P concentration in stems than annual ryegrass in 1998 though no differences were noted among the grasses in 1997 (Table 4). Both oat and rye stems contained a greater amount of P than annual ryegrass stems in 1998.

The P concentrations in leaves of legumes and ryegrass were similar in 1997 (Table 4). In 1998, 8 of 12 legumes had greater leaf P concentration than annual ryegrass. Leaf P concentrations in the grasses were similar both years. All legumes and grasses contained similar amounts of P in 1997 and 1998.

Legume flowers generally had a greater P concentration than annual ryegrass as observed in 9 of 12 legumes in 1997 and 5 of 10 legumes in 1998 (Table 4). The greatest P concentrations noted in any plant part in this study were observed in hairy vetch flowers (8.03 g kg^{-1}) in 1997 and austrian winter pea flowers (9.10 g kg^{-1}) in 1998 (Table 4). However, the DM yield of legume flowers was quite low, resulting in only 0.01 to 0.36 g P m^{-2} in legume flowers. Only crimson clover flowers in 1997 contained more P than annual ryegrass. None of the cereal flowers had a greater P concentration than annual ryegrass in either year (Table 4) though rye flowers contained more P than annual ryegrass in 1997.

Legume roots generally had a higher P concentration than roots of annual ryegrass, with 11 of 12 legumes greater in 1997 and all 12 greater in 1998 (Table 4). The greatest P concentration in roots was observed in subterranean clover (5.36 g kg^{-1} in 1997 and 7.59 g kg^{-1} in 1998). Red clover roots contained more P than annual ryegrass in both years while subterranean clover roots contained more P in 1998.

Averaged over all species, flowers had the greatest P concentration (4.3 g kg^{-1}), followed by leaves (3.1 g kg^{-1}), stems (2.9 g kg^{-1}), and roots (2.7 g kg^{-1}). Minson (1990) reported that forage floral parts had the greatest P concentration (3.2 g kg^{-1}), with little consistent difference in P concentration noted between stems (2.1 g kg^{-1}) and leaves (2.2 g kg^{-1}). In this study, due to the large amount of DM located in stems, most P was contained in stems (0.79 g m^{-2}), followed by leaves (0.34 g m^{-2}), flowers (0.12 g m^{-2}), and roots (0.10 g m^{-2}). To maximize P uptake in sites overfertilized with poultry litter, management procedures and breeding objectives should emphasize stem production to increase the DM to be harvested and removed while maintaining palatability of stems for consumption by livestock.

Potassium

There were few legumes that had greater K concentrations in stems or leaves than annual ryegrass. Stems of ball clover in both years and those of austrian winter pea, hairy vetch, and subterranean clover in 1998 had greater K concentrations than annual ryegrass stems (Table 5). Red and white clover leaves had greater K concentrations than annual ryegrass leaves in 1997 though no difference was found between the species in 1998. Hairy vetch flowers in both years and austrian winter pea and subterranean clover flowers in 1998 had greater K concentrations than annual ryegrass flowers (Table 5). The greatest difference in K concentration between annual ryegrass and the legumes was observed for roots. Eight of 12 legumes in 1997 and 11 of 12 legumes in 1998 had greater root K concentrations than annual ryegrass (Table 5).

Comparisons of K concentration in cereals with annual ryegrass were quite variable. Oat had a greater K concentration in leaves in 1997 and stems and roots in 1998 than annual ryegrass (Table 5). Rye had a greater stem K concentration than annual ryegrass in 1997 but not in 1998.

Few forages contained more K in plant parts than annual ryegrass (data not shown). Rye in both years (6.6 and 8.9 g m^{-2}, respectively) and oat (9.2 g m^{-2}) in

Table 5. Potassium concentration of plant parts of annual ryegrass, three cereals, and 12 legumes.

	1997				1998			
Forages	Stems	Leaves	Flowers	Roots	Stems	Leaves	Flowers	Roots
	g kg^{-1}							
Annual ryegrass	6.6	7.5	14.3	2.2	9.0	14.7	14.6	1.6
Cereals								
Oat	6.7	12.4	9.8	1.7	16.3	13.0	15.3	6.1
Rye	13.6	7.9	29.2	2.5	13.6	9.1	13.1	2.4
Wheat	8.9	7.5	15.8	5.3	9.6	12.1	11.4	4.0
Legumes								
Austrian winter pea	8.5	5.7	14.9	3.9	15.7	15.9	21.3	14.6
Arrowleaf clover	6.8	9.2	21.4	5.6	6.2	7.0	12.3	10.6
Ball clover	12.0	11.1	12.9	6.1	17.1	12.0	15.8	7.1
Berseem clover	4.1	4.9	26.9	4.9	5.0	7.6	–†	6.4
Caley pea	5.9	4.6	13.0	8.2	9.4	8.6	12.3	4.4
Crimson clover	7.2	5.3	21.1	5.2	13.1	12.4	15.8	8.0
Hairy vetch	8.9	12.0	45.4	10.5	16.9	19.2	26.9	11.4
Persian clover	4.5	6.2	12.8	3.3	12.6	6.4	9.2	9.9
Red clover	8.5	14.4	14.5	7.0	9.1	18.9	14.6	9.3
Rose clover	6.4	5.4	10.4	7.5	11.7	10.9	10.7	8.4
Subterranean clover	8.2	9.5	23.1	6.3	16.8	19.0	20.8	5.4
White clover	9.0	18.0	4.8	8.4	8.6	18.1	–	5.9
LSD 0.05	4.0	5.0	14.7	3.1	5.9	5.1	3.2	3.5

† Sample size too small to run K analysis.

1998 contained more K in stems than annual ryegrass (3.8 and 4.7 g m^{-2}, respectively). More K in roots than annual ryegrass (0.3 and 0.2 g m^{-2}, respectively) was observed for red clover in both years (0.8 and 0.6 g m^{-2}, respectively) and oat (0.7 g m^{-2}) and alfalfa (0.4 g m^{-2}) in 1998. Red clover (3.5 g m^{-2}) contained more K in leaves than annual ryegrass (2.0 g m^{-2}) in 1997. Rye (2.4 g m^{-2}) and crimson clover (1.7 g m^{-2}) contained more K in flowers than annual ryegrass (0.4 g m^{-2}) in 1997.

Nitrogen/Phosphorus Ratio

The ideal forage species for nutrient uptake would remove N and P in the same ratio as which it is applied on the soil as poultry litter. Poultry litter has a N/P ratio ranging from 2.0:1 to 2.9:1 while the N/P ratio in crops is generally considered to average 8:1 (NRCS, 1992; Sims and Wolf, 1994; Vest et al., 1996; Patterson et al., 1998). This difference in N/P ratios between litter and crop utilization has been used extensively to illustrate the problem of P accumulation in soils that have been fertilized with poultry litter on the basis of crop N needs (Stephenson et al., 1990; Lucero et al., 1995; Marshall et al., 1998). Yet use of an average value can be misleading as the N/P ratio can be quite different between legumes and grasses or among different forage species. In a compilation of data for four legumes and 18 grasses, the N/P ratio for legumes averaged 10.4 (range 9.1–11.3) and grasses 6.1 (range 1.2–11.5) in the harvested portion (NRCS, 1992). In plant beds for wastewater treatment, the ratio of N to P removal rate for wheat and annual ryegrass was 6.5 while other forage and aquatic species averaged 5 (Abe and Ozaki, 1998).

Legumes had a greater N/P ratio than annual ryegrass in stems in both years, leaves in both years, and flowers in 1998 (Table 6). Roots of legumes did not have a

Table 6. Ratio of N/P content in plant parts of annual ryegrass, three cereals, and 12 legumes.

	1997				1998			
Forages	Stems	Leaves	Flowers	Roots	Stems	Leaves	Flowers	Roots
	N/P ratio							
Annual ryegrass	3.9	8.1	7.9	9.8	4.2	6.6	5.1	11.4
Cereals								
Oat	2.7	7.1	7.7	11.2	2.4	6.0	5.6	3.5
Rye	4.6	10.0	9.1	7.8	3.7	9.1	6.5	8.0
Wheat	4.5	7.7	7.5	9.2	5.1	6.8	6.1	7.3
Legumes								
Austrian winter pea	10.8	14.8	–†	–	6.3	8.8	7.2	8.0
Arrowleaf clover	7.6	14.7	8.5	8.1	7.0	10.3	8.0	7.0
Ball clover	10.4	14.7	7.9	14.8	6.9	10.4	7.1	6.6
Berseem clover	9.2	22.1	8.5	11.1	8.7	16.5	–	11.2
Caley pea	10.2	16.2	15.2	–	8.1	12.9	8.4	10.7
Crimson clover	7.9	18.1	9.9	8.7	5.7	10.7	6.5	6.3
Hairy vetch	11.5	15.3	–	–	6.9	9.8	7.9	9.1
Persian clover	8.7	15.8	7.6	–	7.5	12.4	8.0	6.0
Red clover	8.7	15.4	8.5	8.7	8.1	11.8	9.9	6.0
Rose clover	6.8	16.9	11.3	7.1	7.0	11.4	6.6	5.0
Subterranean clover	3.9	12.1	8.4	5.3	4.2	8.8	7.6	3.0
White clover	8.0	11.0	–	7.6	8.4	7.9	–	6.9
LSD 0.05	2.0	6.3	ns	ns	1.2	3.0	1.6	2.3

† Sample size too small to run N and/or P analysis.

greater N/P ratio than annual ryegrass. The N/P ratio presented for legumes in this study as well as others (NRCS, 1992) includes N contributed by fixation as well as uptake. Therefore, the ratio of N uptake to P uptake for legumes would be assumed to be lower, depending on the relative amount of N taken up by the plant compared with what was obtained through N fixation. None of the cereal plant parts had a greater N/P ratio than annual ryegrass plant parts.

The only N/P ratio that was comparable to poultry litter was that of oat stems (2.7 in 1997 and 2.4 in 1998). Averaged over all grasses, stems (3.9) had the lowest N/P ratio, followed by flowers (6.9), leaves (7.7), and roots (8.5). In legumes, stems (7.9) had the lowest N/P ratio, followed by roots (8.3), flowers (8.6), and leaves (13.6). These results support the previous conclusion in that management procedures and breeding objectives to maximize stem production will not only maximize P uptake, but will also facilitate plant uptake of both N and P in a ratio closer to that of applied poultry litter.

Copper

There were few differences among grass species for Cu concentration as only rye stems had a greater Cu concentration than annual ryegrass stems in 1997 (Table 7). Kubota (1983) also found little variability among grass species for Cu concentration. Most legumes had a greater Cu concentration than annual ryegrass in stems, leaves, and roots in 1997 and leaves, flowers, and roots in 1998. Legume Cu concentration averaged 4.5 to 6.5 times greater for stems, four times greater for leaves, three times greater for flowers, and two to three times greater for roots compared with annual ryegrass plant parts (Table 7). In a review of world literature, Minson (1990) reported that temperate legumes generally have a greater Cu concentration that temperate grasses. Red clover was observed to have a greater Cu concentration than four grass species (Fleming, 1963). Forage legume Cu concentration has been reported to be twice that of forage grasses in the USA (Kubota, 1983) and Canada (Miltmore and Mason, 1971).

Averaged over all species, roots had the greatest Cu concentration (28.8 mg Cu kg^{-1}), followed by flowers (18.1 mg Cu kg^{-1}), leaves (15.5 mg Cu kg^{-1}), and stems (8.4 mg Cu kg^{-1}). Others have reported that roots have a greater Cu concentration than shoots in red clover (Vasseur et al., 1998), willow (*Salix* spp.; Punshon and Dickinson, 1997), *Brassica* spp. (Ebbs and Kochian, 1997), and various wetland plants (Qian et al., 1999). Leaves have also been shown to contain a greater Cu concentration than stems in grasses (Minson, 1990; Fleming, 1963) and legumes (Minson, 1990).

To maximize heavy-metal removal by these forages from poultry litter–fertilized sites, Cu concentration is less important than the total amount of Cu contained within the plant. The large differences observed in Cu concentration between legumes and annual ryegrass did not result in similar differences in the total amount of Cu contained in legumes and annual ryegrass. Only 4 of 12 legumes in 1997 and 2 of 12 legumes in 1998 had greater stem Cu amounts than annual ryegrass (data not shown). Similar results were noted for leaves and flowers. Grass roots averaged 1.01 and 1.81 mg Cu m^{-2} in 1997 and 1998, respectively, while legumes averaged 0.89 and 0.50 mg Cu m^{-2} in 1997 and 1998, respectively. Red clover in 1997 was the only legume to contain more Cu in roots than annual ryegrass. Annual ryegrass contained more Cu in roots than two of three grasses and 6 of 12 legumes in 1997 and two of three grasses and all legumes in 1998.

Plant Cu content was almost the exact opposite of concentration due to the large amount of DM in plant stems and leaves compared with roots and flowers. Averaged over all species, stems contained the most Cu (2.01 mg Cu m^{-2}), followed by leaves (1.57 mg Cu m^{-2}), roots (0.95 mg Cu m^{-2}), and flowers (0.53 mg Cu m^{-2}).

Zinc

Few differences were observed among the grass plant parts for Zn concentration as only rye stems and roots

Table 7. Copper concentration of plant parts of annual ryegrass, three cereals, and 12 legumes.

	1997				1998			
Forages	Stems	Leaves	Flowers	Roots	Stems	Leaves	Flowers	Roots
	mg kg^{-1}							
Annual ryegrass	2.5	4.5	7.5	10.9	1.4	4.8	9.2	16.4
Cereals								
Oats	3.9	5.5	7.9	11.5	1.0	2.1	8.4	7.4
Rye	6.9	5.2	9.0	21.9	2.0	5.9	6.0	21.8
Wheat	3.6	6.1	7.9	7.5	5.1	10.1	8.2	6.1
Legumes								
Austrian winter pea	8.6	17.6	17.5	59.0	8.6	20.6	48.0	62.0
Arrowleaf clover	7.4	13.4	21.9	27.0	6.1	13.1	24.8	31.8
Ball clover	6.9	11.9	21.2	18.2	6.0	18.9	27.0	29.9
Berseem clover	10.6	21.9	24.1	31.8	9.1	34.5	–†	52.5
Caley pea	16.4	25.0	22.3	50.0	8.9	17.2	21.2	91.0
Crimson clover	9.9	12.6	13.2	29.1	4.2	15.5	25.2	26.7
Hairy vetch	9.9	20.0	23.5	23.8	9.1	20.5	35.0	14.5
Persian clover	7.0	20.2	18.5	32.8	8.4	20.0	41.0	44.5
Red clover	8.6	16.1	20.2	24.2	3.8	14.0	20.2	16.5
Rose clover	6.5	13.5	9.8	20.1	4.5	16.2	14.0	30.5
Subterranean clover	19.1	23.6	26.6	42.2	22.4	25.8	24.8	33.9
White clover	20.2	12.0	38.0	28.4	20.1	16.5	–	28.4
LSD 0.05	3.1	6.4	5.7	11.0	8.5	6.9	12.0	11.8

† Sample size too small to run Cu analysis.

Table 8. Zinc concentration of plant parts of annual ryegrass, three cereals, and 12 legumes.

Forages	1997 Stems	1997 Leaves	1997 Flowers	1997 Roots	1998 Stems	1998 Leaves	1998 Flowers	1998 Roots
	mg kg^{-1}							
Annual ryegrass	24.5	17.9	25.4	33.6	31.9	46.0	61.0	60.8
Cereals								
Oats	20.9	12.5	25.8	56.2	33.4	27.0	40.6	50.1
Rye	51.2	14.4	18.6	79.1	33.6	38.1	37.8	92.0
Wheat	28.0	19.5	20.1	17.6	33.0	43.5	54.8	47.2
Legumes								
Austrian winter pea	57.1	79.4	53.2	29.0	80.8	183.2	177.0	123.0
Arrowleaf clover	31.2	42.0	51.5	36.5	39.0	81.0	83.8	86.6
Ball clover	43.5	47.6	68.7	55.9	73.6	136.1	142.5	120.6
Berseem clover	38.0	44.4	53.1	81.9	60.6	118.5	–†	159.5
Caley pea	73.4	163.5	64.0	53.5	38.4	115.6	69.0	147.0
Crimson clover	37.6	38.6	28.8	36.4	41.5	81.0	83.2	64.5
Hairy vetch	53.0	117.8	82.2	46.8	70.2	166.9	139.2	36.0
Persian clover	28.0	53.0	76.8	35.5	74.4	100.5	168.0	129.0
Red clover	17.0	37.5	44.3	26.4	19.2	47.0	55.8	30.6
Rose clover	34.1	58.8	21.4	32.9	48.4	135.1	64.0	74.5
Subterranean clover	47.0	92.4	60.8	48.8	81.8	143.8	75.8	92.5
White clover	54.2	38.9	27.0	43.8	56.9	73.5	–	62.0
LSD 0.05	20.5	28.6	22.7	29.5	18.0	37.5	20.0	38.8

† Sample size too small to run Zn analysis.

had greater Zn concentrations than annual ryegrass in 1997 (Table 8). Gladstones and Loneragan (1967) observed Zn concentration in rye shoots similar to that in wimmera ryegrass (*Lolium rigidum* Gaud.) but greater than wheat or oat shoots. Minson (1990) noted that several studies have reported large differences in Zn concentration among grasses, but these differences were not consistent among sites.

Many of the legumes evaluated had greater Zn concentrations than annual ryegrass for all plant parts except roots in 1997 (Table 8). Legume Zn concentrations were almost two times greater in stems, 2.5 to 3.5 times greater in leaves, and two times greater in flowers compared with annual ryegrass plant parts. Previous results on Zn concentration differences between grasses and legumes have not been consistent. Minson (1990) and Metson et al. (1979) reported that legumes had slightly greater Zn concentrations than grasses while Gladstones and Loneragan (1967) observed much greater Zn concentrations in legumes than grasses and cereals. The greatest Zn concentrations in 1997 were located in caley pea stems and leaves, hairy vetch flowers, and berseem clover roots while in 1998, austrian winter pea stems, leaves, and flowers and berseem clover roots had the greatest concentration (Table 8).

When Zn concentrations were averaged over all species, leaves had the greatest concentration (75.4 mg Zn kg^{-1}), followed by flowers (65.8 mg Zn kg^{-1}), roots (65.3 mg Zn kg^{-1}), and stems (40.5 mg Zn kg^{-1}). Other studies have reported Zn concentrations of leaf and flower greater than those of stems for a number of grasses and legumes (Minson, 1990; Fleming, 1963).

Few differences were noted for Zn uptake between annual ryegrass and any of the other forages (data not shown). Subterranean clover leaves were the only plant part to contain more Zn than annual ryegrass in both years. Rye stems in 1997; ball, crimson, red, and rose clover leaves in 1997; and rose clover flowers in 1998 also contained more Zn than annual ryegrass. These results differ from those of Gladstones and Loneragan (1967), who observed much greater Zn uptake in legume shoots than grass or cereal shoots.

As was observed for Cu, Zn uptake was closely related to relative DM production of the different plant parts, with stems containing the most Zn (12.4 mg Zn m^{-2}), followed by leaves (7.0 mg Zn m^{-2}), roots (2.4 mg Zn m^{-2}), and flowers (1.9 mg Zn m^{-2}).

Correlations

Nitrogen, P, Cu, and Zn concentrations were highly correlated for all aboveground plant parts in both years of this study (Table 9). For roots, N, P, and Cu concentrations were correlated as well as N and K concentrations. Little consistent relationship was noted between K and P (Table 9). No correlation was found between K and P concentration for any plant part in 1997, yet in 1998, all plant parts showed a significant correlation. Strategies to improve N concentration through management or breeding should also result in increases in P, Cu, and Zn concentration. Nitrogen fertilization is one management technique known to improve N concentration in grasses. Therefore, to improve P, Cu, and Zn concentration and uptake in poultry litter–fertilized sites, it may be beneficial to apply limited amounts of N fertilizer to annual ryegrass or other grasses when N is not in excess.

CONCLUSIONS

Hay production and sale off-farm is a viable method for removing excess nutrients from litter-treated pastures. Other harvesting methods, such as silage, green chop, and baleage, will also remove nutrients though, due to transportation costs, movement of these materials is usually limited to the local area. Often other local cattle producers without access to litter may be able to reduce fertilizer costs by utilizing excess P and K obtained through manure from cattle fed hay harvested from litter-treated fields. Markets, in areas such as commercial mulch or home gardening, should be developed

Table 9. Linear correlation coefficients of N, P, K, Cu, and Zn concentration for plant parts of 16 forages.

Plant part	Nutrient concentration		Correlation coefficients 1997	1998
Stems	N	P	0.38**	0.65**
	N	K	0.01	0.18
	N	Cu	0.81**	0.57**
	N	Zn	0.60**	0.63**
	P	K	0.07	0.52**
	P	Cu	0.61**	0.45**
	P	Zn	0.26*	0.59**
	K	Cu	−0.03	−0.01
	K	Zn	0.01	0.36**
	Cu	Zn	0.61**	0.46**
Leaves	N	P	0.37**	0.76**
	N	K	−0.01	0.23
	N	Cu	0.67**	0.66**
	N	Zn	0.67**	0.70**
	P	K	0.04	0.53**
	P	Cu	0.08	0.60**
	P	Zn	0.33**	0.73**
	K	Cu	−0.14	0.24
	K	Zn	−0.19	0.23
	Cu	Zn	0.73**	0.74**
Flowers	N	P	0.76**	0.86**
	N	K	0.28	0.54**
	N	Cu	0.82**	0.69**
	N	Zn	0.59**	0.69**
	P	K	0.14	0.66**
	P	Cu	0.48**	0.62**
	P	Zn	0.84**	0.72**
	K	Cu	0.25	0.30*
	K	Zn	−0.24	0.37*
	Cu	Zn	0.45**	0.82**
Roots	N	P	0.76**	0.67**
	N	K	0.38*	0.57**
	N	Cu	0.69**	0.82**
	N	Zn	−0.01	0.29*
	P	K	0.23	0.35*
	P	Cu	0.59**	0.31*
	P	Zn	0.16	0.11
	K	Cu	0.25	0.22
	K	Zn	−0.21	−0.01
	Cu	Zn	0.21	0.76**

* Significant at the 0.05 level.
** Significant at the 0.01 level.

for poor quality hay or hay containing excessive nutrient levels that could adversely affect animal health. As the levels of nutrients rise in litter-treated pastures, producers need to be creative in attacking this problem.

Annual ryegrass is the most common winter annual forage grown in the southeastern USA. In fields fertilized with poultry litter, annual ryegrass was as effective as other forages in N, P, K, Cu, and Zn uptake. Few other species showed significant advantages over annual ryegrass for whole-plant nutrient uptake. The low N/P ratio of oat stems and greater P content in 1998 could make oat a possible alternative to annual ryegrass in some areas less sensitive to frost. The concentration of DM in stems emphasizes the importance of optimizing stem production to maximize nutrient uptake by annual ryegrass and other forages. Annual ryegrass breeding programs have usually concentrated on grazing uses with selections for disease resistance, forage quality, and variation in plant maturity (Jung et al., 1996). Selections for grazing tolerance and forage quality may result in short, leafy plants with less DM in stem production. Our results suggest that plants should be selected or managed for DM yield, with a greater proportion of their DM in stems to maximize nutrient uptake. If the end use of the forage is livestock consumption, producers need to still maintain acceptable palatability in the hay.

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